Evaluation of Ultrafast Recording Technologies for Reduction to Practice

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This project addresses limitations of technologies presently used for single-shot, transient recording of ultrafast signals. Current instrumentation relies on high-bandwidth oscilloscopes, streak cameras, and Frequency Resolved Optical Gating (FROG) methods. The performance associated with these solutions is fundamentally limited and will fail to support upcoming programmatic requirements. The best candidate for achieving these requirements is a hybrid technology implementing 1) an all-optical sampler that routes serial signals into parallel channels at timescales approaching 1 ps, followed by 2) detection with an array of high-dynamic-range integrating detectors.

This strategy circumvents the limitations (Fig. 1) of current methods in an analogous manner to hybrid communication strategies involving both serial optical time division multiplexing (OTDM) and parallel wavelength division multiplexing (WDM) for the high-bandwidth transmission of information. Recent progress in nonlinear optics, driven by the new fast all-optical switching technologies for telecommunications applications, has achieved a critical maturity. However, the lack of obvious commercial applications for high-fidelity single-shot transient recording technologies has limited progress in this approach thus far.

Project Goals

We aim to conduct an initial scoping and exploration of a technology area that has high strategic potential for LLNL missions. Specifically, we seek to compare selected classes of integrated microphotonic devices that can be tailored to implement ultrafast nonlinear optical switching phenomena. We plan to construct a framework and supplementary modeling tools required to uncover the nonlinear optical materials, fabrication processes, and photonic architectures optimally suited to handle next-generation instrumentation requirements.

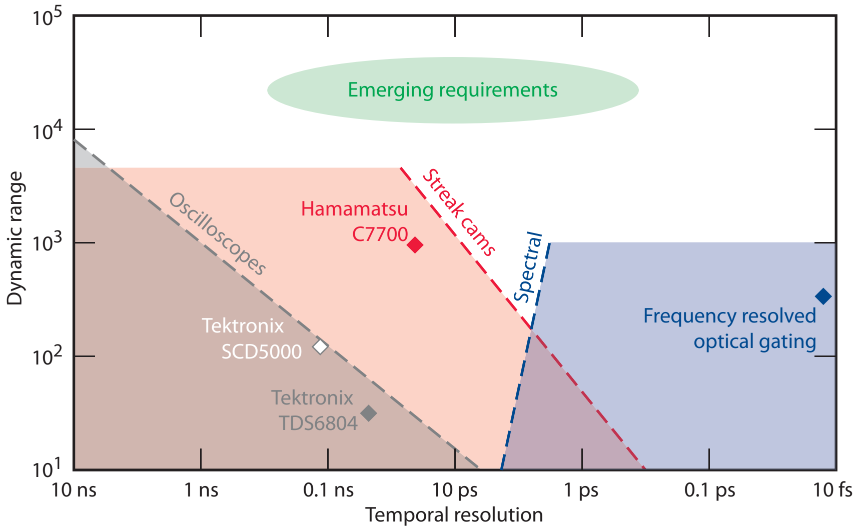

Figure 1. Parameter space (dynamic range vs. speed) of existing recording technologies and emerging LLNL HEDS/NIF requirements.

Relevance to LLNL Mission

The work directly addresses instrumentation performance gaps identified by LLNL. Specifically, future HEDS (high-energy-density science) experiments on NIF will demand transient recording technology possessing high temporal resolution (< 10 ps), high dynamic range (> 1000:1), and scalability to multichannel geometries. No existing recording technology satisfies these demanding requirements simultaneously.

The implementation of all-optical sampling mechanisms for ultra-high-fidelity transient recording represents a radical but promising departure from conventional recording technologies. The characterization of ultrashort laser pulses would benefit directly from this technology. Furthermore, when coupled with LLNL-pioneered radiation-to-optical encoding technology, a potential replacement for aging radiation–sensitive transient recording instrumentation is feasible.

FY2006 Accomplishments and Results

Nonlinear optical phenomena that result in the optically-induced modification of the refractive index of a solid-state material include (Fig. 2) the optical Kerr and Stark effects, the plasma effect, exciton screening, the bandfilling (Burstein-Moss) effect, and the bandgap shrinkage effect. All-optical switches that route a light signal in proportion to the intensity of a secondary (control) light source can be engineered from these phenomena through a variety of mechanisms. In practice however, due to the relatively weak nature of nonlinear optical interactions, nonlinear optical engineering lags nonlinear electrical engineering (*i.e.*, electronics) by some 50 years. Thus, applications of this promising technology with relevance to optical sampling are posed with the following challenges:

1. The subset of materials that display substantial nonlinear optical response and maintain compatibility with state-of-the-art integration technologies is limited primarily to III-V semiconductors.
2. The effective speed of the signal sampling will depend on the material response times (rise and recovery), inter-gate propagation delays, and structured resonance bandwidths.
3. The attainable dynamic range of the instrument will be further corrupted in practice by optical leakage and cross-talk at each of the sampling gates due to fabrication imperfections, control pulse instabilities, and control beam nonuniformities.

To address these challenges, a major component of our study consisted of the detailed investigation and identification of architectures that implement materials with high nonlinear figures of merit and compatibility with integration technologies for which LLNL carries strong expertise. We furthermore sought an all-optical sampling mechanism that displays a strong, ultrafast response, and is robust to the fabrication errors, pulse instabilities, and beam nonuniformities expected to be encountered in reasonably toleranced systems.

We down-selected from among multiple architectures to a deflection encoded geometry that implements bandfilling and plasma effects in III-V semiconductors. In direct analogy to electron-based oscilloscopes and streak cameras, the down-selected architecture deflects an optical beam onto a high-dynamic-range detector array or camera for subsequent recording.

Related References

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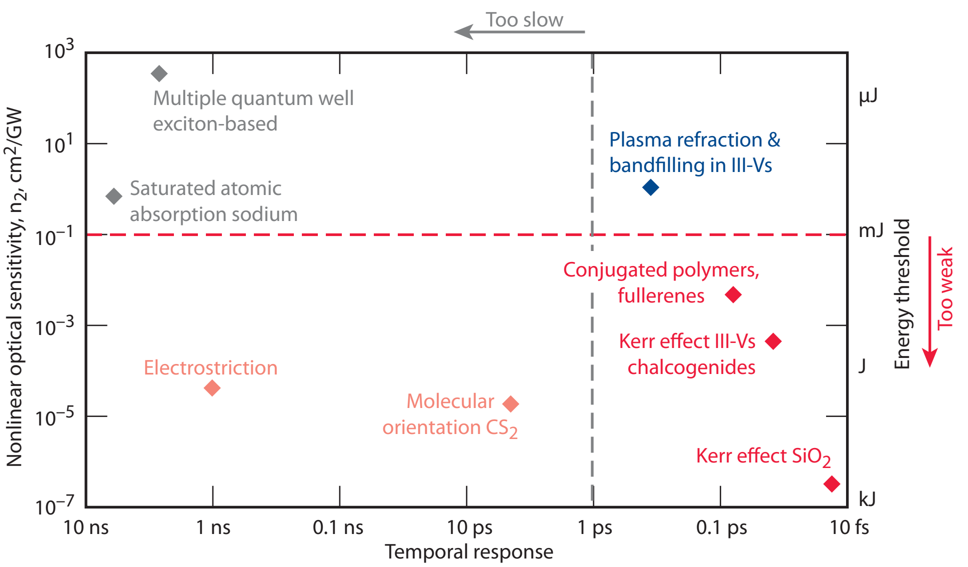

Figure 2. Parameter space (sensitivity vs. speed) of existing nonlinear optical sampling mechanisms in solid-state materials capable of modifying optical properties on a fast timescale.